# EXPLORING THE KUIPER BELT:
# AN EXTENDED PLUTO MISSION

PAUL K. HENRY[1], RICHARD J. TERRILE[2], ROBERT W. MADDOCK[3],
and HAROLD R. SOBEL[4]

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA

**Abstract** - A robotic flyby mission to the planet Pluto is being planned for launch early in the next decade. The spacecraft will continue on out of the solar system in an almost radial direction traveling at about four AU per year and begin transiting the Kuiper Belt shortly after Pluto encounter. Recent discoveries and observations of Kuiper Belt objects have generated increased interest in the characteristics of these bodies. This paper examines the opportunities and requirements for extending the Pluto mission to include the search for, and encounters with, objects in the Kuiper Disk at 40+ AU. The trajectory and $\Delta V$ requirements will be presented. An automated, on-board sky survey will be proposed to inventory the Kuiper objects in the vicinity of the flight path and to identify which objects are candidates for altering the trajectory for a close flyby. A possible Kuiper object encounter science scenario will be described.

## 1. INTRODUCTION

In December of 2004, NASA plans to launch a spacecraft to perform the first reconnaissance of the planet Pluto and its moon Charon. The flight time could be as long as 16 years or as short as 8 years depending on the launch vehicle and launch date chosen. Following the Pluto encounter, the spacecraft will continue out of the solar system along a trajectory that carries it into the Kuiper Belt at speeds up to 4.1 AU/year, again depending on the launch vehicle.

In this discussion, the trajectory to Pluto and beyond will be described. We will describe the capabilities of the Pluto imager and examine the likelihood that it will be able to detect objects of different sizes and at what distance. A rough estimate of the number of objects that can be detected between 30 AU and 50 AU will be given. Finally, a scenario for a close encounter with a KBO will be described.

1 Science Payload Lead, Outer Planets/Solar Probe Project
  paul.k.henry@jpl.nasa.gov
  Tel:818-354-3106, Fax:818-393-4773
2 Project Scientist, Outer Planets/Solar Probe Project
  richard.j.terrile@jpl.nasa.gov
  Tel: 818-354-6158, Fax: 818-354-0966
3 Mission Design Analyst, Outer Planets/Solar Probe Project,
  robert.w.maddock@jpl.nasa.gov
  Tel:818-354-1443, Fax:818-393-9815
4 Instrument Performance Analyst, Observational Systems
  Division, harold.r.sobel@jpl.nasa.gov
  Tel:818-354-4526, Fax:818-393-4489

## 2. SCIENTIFIC IMPORTANCE OF THE KUIPER BELT

Recent observations of the Kuiper Belt from the Hubble telescope and large ground-based telescopes such as the Keck have resulted in a growing interest in the Kuiper Belt and its role in the formation of the Solar System. The Committee on Planetary and Lunar Exploration (COMPLEX) recently recommended that the Pluto mission be extended to include encounters with Kuiper Belt objects (KBO) to image them and characterize the surface composition of the various KBO types [1].

As of the time of preparation of this paper, some 64 objects have been classified as "transneptunian." These objects orbit the Sun beyond Neptune, outward from 30 AU to perhaps 100 AU or more, and within a few degrees of the ecliptic thus forming a ring that has come to be called the Kuiper Belt. These objects are thought to be primitive remnants of the early formation of the solar system. Knowledge of their size and mass distribution, and their composition would be of great value in understanding the evolution and dynamics of the solar system. In addition, the Kuiper Belt is widely thought to be the reservoir for the short period comets.

## 3. THE PLUTO-KUIPER EXPRESS TRAJECTORY

### 3.1 Pre-Pluto Encounter Accessibility to Kuiper Belt Objects

The Jupiter Gravity Assist (JGA) trajectory currently being used as the baseline for the PKE mission (Fig. 1) has
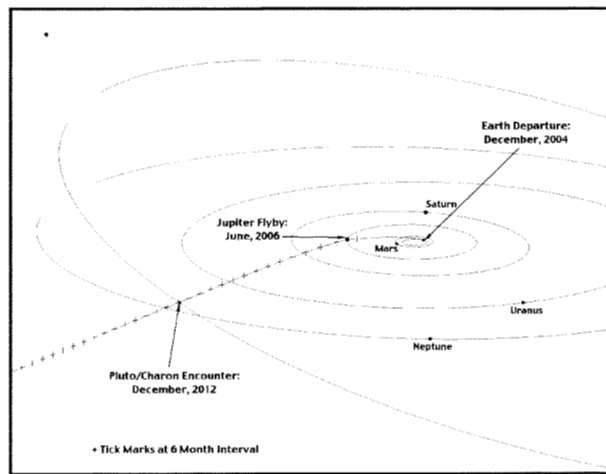
*Figure 1.* Pluto-Kuiper Express 2004 Jupiter Gravity Assist Trajectory.

a fairly simple trade space : the longer the flight time, the lower the launch system requirements. This means that by increasing the flight time, the spacecraft mass is allowed to increase as well. This trade between flight time and spacecraft mass also affects the Pluto relative flyby velocity (i.e., $V_\infty$) and thus the spacecraft heliocentric velocity at Pluto. This velocity trade has a significant impact on what the spacecraft can do and where it can go in the Kuiper Belt after the Pluto/Charon encounter.

By adjusting the aim point in the B-plane, the outgoing vector can be changed by a small amount for targeting a KBO. Due to the small mass of Pluto itself, as well as the large relative velocity, the spacecraft trajectory is only minimally affected by the gravity of Pluto. The deflection angle of any planetary flyby can be approximated by :

$$\Psi = 2\sin^{-1}\left[\cfrac{1}{1+\left(\cfrac{d+R_p}{\mu}\right)V_\infty^2}\right]$$

where $\psi$ is the deflection angle, $d$ is the miss distance or closest approach altitude, $R_p$ is the planet radius, $\mu$ is the universal gravitational constant times the planet mass (GM), and $V_\infty$ is the spacecraft hyperbolic excess speed (spacecraft relative velocity w.r.t. the planet at infinity). The equation above shows that the trajectory deflection from Pluto will be driven by the flyby altitude as well as the flight time which determines the $V_\infty$. Figure 2 below shows the deflection angle as a function of closest approach altitude for the 2004 JGA trajectory with an 8 year flight time to Pluto, the flight time that we will use as the basis for this discussion. Other encounter requirements such as achieving sun and Earth occultations might preclude large changes in the Pluto encounter geometry.

### 3.2 Post-Pluto Encounter Accessibility to Kuiper Belt Objects

After the Pluto/Charon encounter, the only method of changing the spacecraft trajectory in order to aim at a possible Kuiper object is for the spacecraft to execute a targeting maneuver using its own propulsion system. Again,
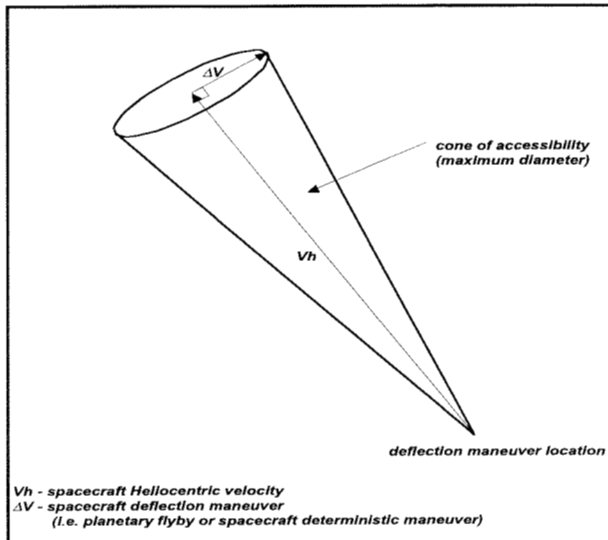

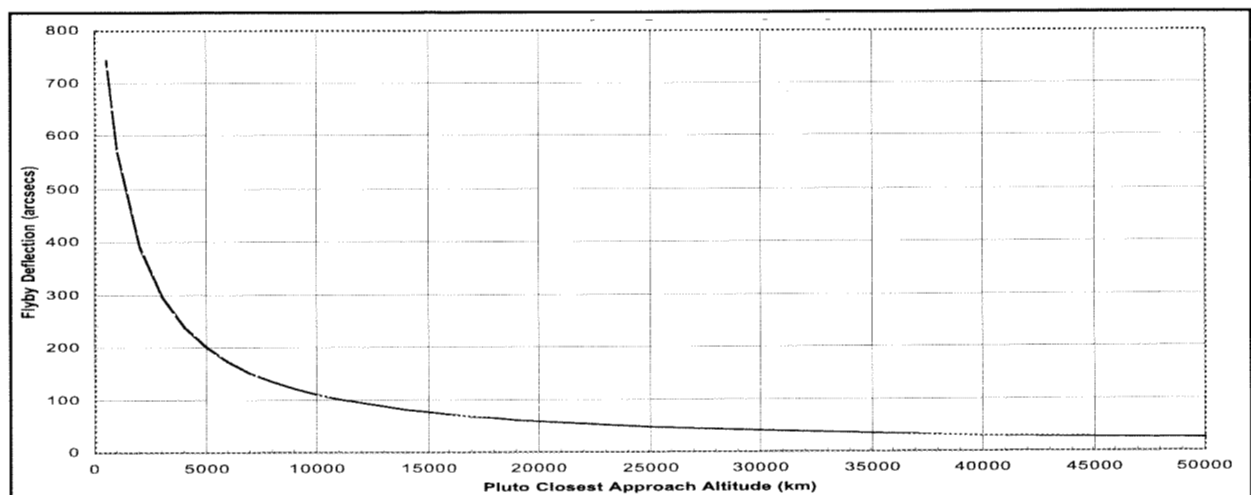
*Figure 3.* Spacecraft Deflection - Cone of Accessibility



*Figure 2.* Pluto Gravity Assist Deflection Angle vs. Closest Approach Altitude (PKE 2004 JGA - 8yr. flight time trajectory).
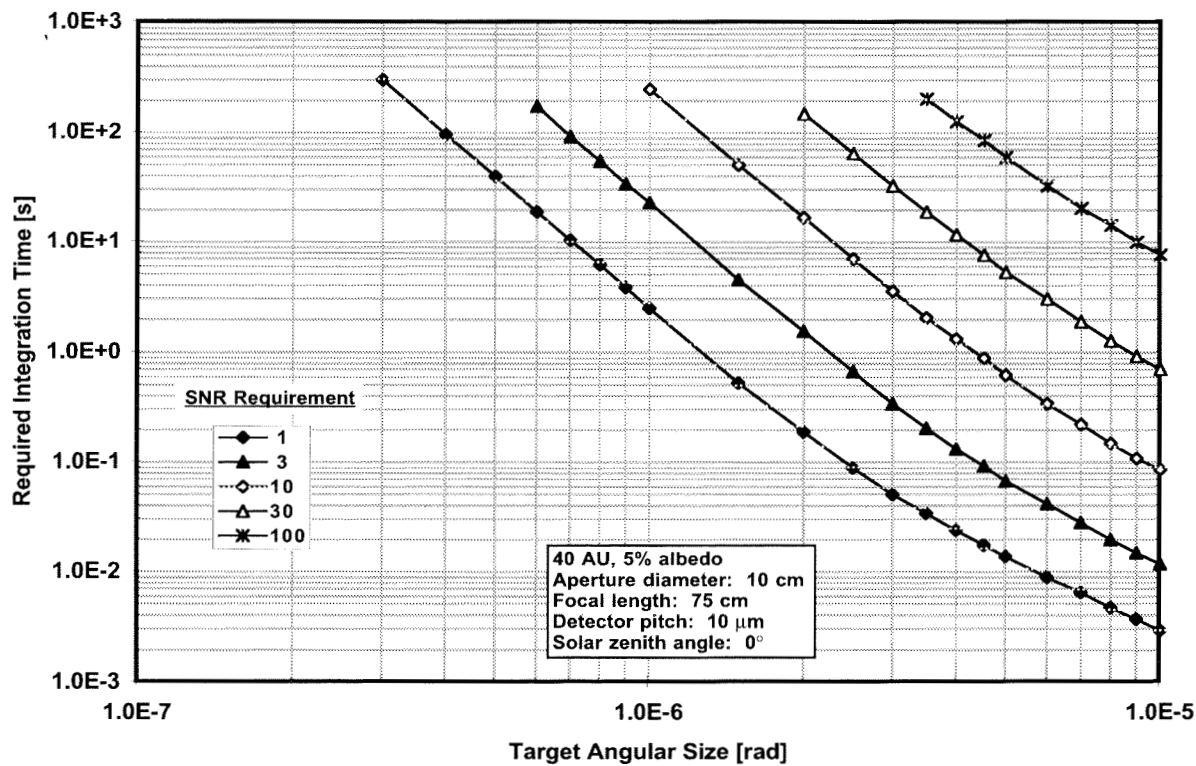
**Figure 4.** Integration Time Required to Achieve a Given Signal-to-Noise Ratio as a Function of KBO Angular Size.

the effect of this maneuver is influenced by the spacecraft velocity: the faster the spacecraft is moving, the more propellent required to provide a desired deflection.

Once a KBO has been detected, it must quickly be determined if it is a candidate for a close flyby and what propulsive maneuver would be required to execute the encounter. At any point in time there is a maximum angle through which the spacecraft flight path can be deflected. This angle is simply the arctangent of the remaining $\Delta V$ divided by the spacecraft velocity. Analysis indicates that the remaining $\Delta V$ after Pluto encounter could be 20-60 m/sec ($1\sigma$). Assuming a post-encounter outgoing heliocentric velocity of 19.3 km/sec, the maximum accessible Kuiper Belt volume is defined by a cone extending downtrack, of apex half-angle arctan $\Delta V/V_h$ as shown in Fig 3. We call this the "cone of accessibility." Of course, the $\Delta V$ probably would not be expended in a single maneuver and the timing of the maneuvers would depend on the targets to be intercepted. So the cone of accessibility is temporal and dynamic, and depends on whether it is pre- or post-Pluto encounter, the timing of maneuvers and the subsequent remaining propellant.

## 4. IN-FLIGHT DETECTION OF KUIPER BELT OBJECTS

### 4.1 Detection Distance

The current Pluto spacecraft includes a radio science experiment, a XUV airglow and solar occultation spectrometer, a visible, multi-color imager, and a high spectral resolution IR imaging spectrometer. The latter two instruments are most useful for observing Kuiper Belt objects.

First we will estimate the distance at which a Kuiper Belt object can be detected by the on-board imager. We assume an on-board telescope and detector that has the capability to meet the science objectives of the Pluto encounter [2]. Table 1 summarizes the imager and observation parameters used in estimating the maximum detection distance. For purposes of calculating signal to noise

**Table 1.** Imager Parameters and Assumptions for Calculating Integration Times and Signal-to-Noise Ratios.

| Solar Distance | 40 AU |
|---|---|
| Albedo | 0.05 |
| Zenith angle | 0° |
| Aperture diameter | 10 cm |
| Effective focal length 75 cm | 75 cm |
| Instrument IFOV | $1.33 \times 10^{-5}$ radian |
| Obscuration in the telescope | 15% area obscuration 38.7% linear obscuration |
| Optics transmittance | 0.729 (3 mirrors @ 0.9 reflectivity ) |
| Fraction of energy on pixel from point source | 0.5 |
| Detector type | Active Pixel Sensor (APS) |
| Pixel pitch | 10 μm |
| Read noise | 5 electrons |
| Quantum efficiency | peak of ~0.6 at ~0.65 μm (see plot) |
| Dark current density | 150 pA/cm^2 = 936 e-/sec for a 10 μm square pixel |
| Full well | 3E+5 electrons |
| Time to saturate with dark current | 320 sec |

ratios (SNR) and integration times, we assume that the observation occurs at 40 AU and the object has an albedo of 0.05.

Given the observation parameters in Table 1, the integration time required to attain a given signal-to-noise ratio can be calculated as a function of target angular size. This result is shown in Figure 4 for SNR = 1, 3, 10, 30, 100.

**Table 2.** Constraints on the Kuiper Belt Population [4]

| Source | Radius (km) | Number 30<r<50 AU | Reference |
|---|---|---|---|
| 1. Short-period comet supply | $1 \leq R \leq 10$ | ~ 5 X $10^9$ | Duncan, et al (1995) [5] |
| 2. HST Observations | $5 \leq R \leq 10$ | > 2 X $10^8$ | Cochran, et al (1995) [6] |
| 3. Pluto-Charon perturbers | $R \geq 20$ | < 3 X $10^8$ | Levison and Stern (1995a) [7] |
| 4. Ground-based searches | $50 \leq R \leq 200$ | > 3.5 X $10^4$ | Jewitt and Luu (1995) [8] |
| 5. Pluto | R > 1000 | 1 | Tombaugh (1961), [9] Kowal (1989) [10] |

For example, if we assume that we integrate for 20 seconds and require a SNR = 3 to detect a KBO moving against the star background, then from Figure 4, we can detect objects of 1 microradian in angular size. The actual size of the object is just the product of the angular size and the distance to the object. For example, a 100 km diameter object at $100 \times 10^6$ km would subtend an angle of 1 μ-radian and be detectable with a SNR = 3.

### 4.2 Observable Kuiper Belt Volume and Number of Observable Objects

With the on-board telescope described above, what is the maximum volume of the Kuiper Belt that can be explored by the Pluto-Kuiper mission? Also, how likely is it that there will be Kuiper Belt objects in the volume of space in which various size objects of can be observed from the spacecraft?

**Table 3.** Estimates of the number of Kuiper Belt Objects that would be observable with SNR=3 from the spacecraft as it transits the Kuiper Belt between 30 AU and 50 AU. Results for two integration times as shown, 20 seconds assuming an articulated mirror to offset spacecraft drift, and 1 second assuming the imager optic axis is body-fixed to the spacecraft.

| KBO Radius (km) | Radius of Observable Volume (AU) | Observable Volume at SNR=3 from Fig. Between 30-50AU (AU³) | Avg. Number KBO/Volume (Objects/AU³) | Avg. Number Objects in Volume Observable From Spacecraft (Objects) |
|---|---|---|---|---|
| 1 < R < 10 (Assumed 5 km) | 0.07* 0.03** | 0.28* 0.06** | 93700 | 26400* 5657** |
| 5 < R < 10 (Assumed 10 km) | 0.13* 0.06** | 1.13* 0.23** | 3748 | 4230* 876** |
| R > 20 (Assumed 20 km) | 0.27* 0.12** | 4.48* 0.94** | 5622 | 25200* 5256** |
| 50 < R < 200 (Assumed 100 km) | 1.34* 0.6** | 113.5* 23.4** | 0.6 | 72* 15** |
| | *20 second integration time | | **1 second integration time | |

The answers to these questions depend on the size and population distribution of Kuiper Belt objects. Table 2 [4] shows the constraining population estimates from various sources for different size objects in the Kuiper Belt between 30 AU and 50 AU. A rough estimate of the average number of objects of a given size range per $AU^3$ can be obtained by assuming the belt subtends a heliocentric angle of about ±7.5 degrees about the ecliptic and calculating the volume between 30 and 50 AU. This yields a volume of about $5.3 \times 10^4$ $AU^3$. This can be divided into the populations in Table 2 to give a rough average number of objects per $AU^3$. These average population densities are shown in the fourth column of Table 3.

Now we calculate the total volume of space in which objects of the size of KBOs are detectable from the spacecraft. The volume can be visualized as tubes through the Kuiper Belt, concentric about the flight path, and the radii of which are the maximum distance at which objects of different sizes can be detected. A rough estimate of the number of objects of different sizes that may be observable can be obtained by comparing the observable volume to the average number of objects per volume. This is shown in the fifth column of Table 3. The somewhat counter-intuitive result that there would be substantially more observable objects of 20 km radius than 10 km radius is an artifact of the very similar populations listed in Table 2 and the larger observable volume for the larger object, and the fact that the populations in Table 2 are independent estimates from different sources.

The results shown in Table 3 indicate that the extended mission to the Kuiper Belt has a high likelihood of observing objects in every size category including, of course, Pluto and Charon.

Once the propellant is completely expended, the observable volume then becomes a cone of decreasing radius as distance from the sun increases, i.e., an object of a given size must subtend a larger angle to be observable. This progression reaches extinction when there is no longer sufficient illumination for the imager to detect a reflected signal with sufficient SNR. For a 20 second integration time and a SNR = 3, that distance is a rather amazing 580 AU, or 270 AU for a 1 second integration time, well beyond the projected lifetime of the spacecraft.

## 5. EARTH-BASED SEARCH OF THE CONE OF ACCESSIBILITY

Once the Pluto encounter parameters have been firmly established, at about encounter minus 2 years, a detailed Earth-based search of the pre-encounter cone for KBOs should be conducted. Upgrades to the Hubble Telescope, the deployment of the next generation space telescope, large ground telescopes, and the advent of long baseline interferometers will permit a much more thorough search of the region than is now possible.

## 6. AUTONOMOUS SEARCH MODES

The highly capable Pluto-Kuiper Express spacecraft on-board computer system presents the opportunity to migrate complex new software from the ground to the spacecraft. This takes advantage of software and data processing advancements in the 15+ years between spacecraft design and spacecraft transit of the Kuiper Belt [3]. Since, at 40 AU, the round trip light time is 11 hours, it is anticipated that the routine KBO searches will be conducted autonomously by the spacecraft.

### 6.1 Autonomous Search With Spacecraft Body-Fixed Pointing

The search scenario depends heavily on how the Pluto mission imaging system is implemented. If the viewing axis is body-fixed to the spacecraft and relies entirely on the spacecraft attitude control system for pointing, the search modes are severely restricted by spacecraft stability and attitude control propellant usage. In this case, the searches would consist of periodic sweeps of the star fields in the down-track direction. A pattern of spacecraft attitude slews would be performed to image the sky ahead, and store the images on-board. Some interval of time later the pattern would be repeated and the images compared, also on-board. To conserve propellant, it may be possible to nutate the spacecraft about the velocity vector to achieve a continuous, but limited angle scan of the region ahead, although this would severely limit the useful integration times.

If no candidate objects are identified, the system does not repeat the search pattern until some specified time later, probably days to tens of days, depending on how much propellant is required for each search. However, if a candidate KBO is identified, the spacecraft will immediately slew to the appropriate attitude to image the object and once acquired, keep the object in the imager field of view for repeated imaging against the star background. Knowing the velocity vector of the spacecraft and how the KBO moves against the star background, an estimate of the KBO's size and orbital velocity vector can be obtained. Then it would be ascertained if the KBO is within the cone of accessibility at that point in time, and if it meets the criteria to initiate an intercept $\Delta V$ maneuver for a close encounter.

As part of determining whether or not a KBO is a candidate for a close flyby, the on-board computer will examine the required intercept trajectory, determine timing, direction and magnitude of the propulsive maneuver required. The requirements will be judged against a set of decision criteria stored on board. The criteria will include such factors as propellant required compared to propellant remaining, desirability of the post-maneuver trajectory, size of the object, spectral signature of the object, uniqueness or similarities compared to previously observed objects, and imaging resolution at closest approach. These criteria will be updated as the Kuiper mission progresses to reflect the accumulated knowledge and interest at the time.

As an example, consider the case of a 40 km diameter object. If we assume that it can be detected at a SNR = 3, then it will be detected with a 20 second integration time at a distance of $40 \times 10^6$ km. If the spacecraft is traveling at 19.3 km/sec, and the object is nearly downtrack, the object will be observable for about 24 days before closest encounter. Let us assume that the decision criteria stored on-board determines that the object has characteristics that make it interesting enough to expend, say, 15 m/sec of the remaining propellant to execute a close flyby. This would

result in a maximum cross-track deviation of about $3.11 \times 10^4$ km. The spacecraft would execute the course change only if the object is within a cone of accessibility defined by a 15 m/sec maneuver and all other criteria are met.

Note from Figure 3 that the maximum Post-Pluto deflection is about 3 mrad assuming 19.3 km/sec velocity and 60 m/sec $\Delta V$, giving a cone of accessibility 6 mrad wide. Since the imager is expected to have a square 10 mrad field of view, the cone of accessibility can fall entirely within a single image. This enables the normal search mode for objects that are candidates for close encounter to be simply the comparison of successive images looking straight ahead along the flight path.

### 6.2 Autonomous Search With Active Instrument Pointing

If the imager viewing axis is not spacecraft body-fixed, for example by employing a precision pointing mirror with a large field of regard, the flexibility and productivity of the KBO search is substantially improved. The frequency and angular range of search can be increased with little or no increase in propellant expenditure. The basic approach to the search sequence is the same as for the body-fixed case, but with the mirror providing the search pattern instead of spacecraft slews. Another benefit of a precision pointing mirror is the ability to determine spacecraft drift rate to a very high precision and then drive the mirror to offset that rate. This permits much longer imager integration times to obtain unsmeared deep exposures. This will be especially critical to the IR observations for KBO composition. The effect is to extend the detection limit to smaller and/or more distant objects or raise the SNR and reduce the number of false KBO detections. This would also enable the detection of the weaker spectral signals from minor compositional constituents and, in close encounter, compensating for image motion from the relative velocities of the spacecraft and KBO.

## 7. KUIPER BELT OBJECT ENCOUNTER SCENARIO

After the maneuver to intercept is performed, the KBO will be tracked by the imaging system to continuously improve the ephemeris. The best estimate of close encounter parameters such as position, range, relative velocity vector, and phase angle will be updated at regular intervals. These parameters will drive the instrument pointing and the timing of the data acquisition sequence. Both visible and infrared images will be recorded and stored at regular intervals as the resolution increases. Images will be compared over time to determine the rotation rate and axis of the KBO, and the range from the rate of increase in angular size. The timing of the near-encounter observational sequence will be keyed to the KBO rotation rate and modified in real time to maximize the surface coverage. Following close encounter, the object will be tracked as long as possible to improve the ephemeris. In most cases, this will be a short time since phase angle will be increasing rapidly.

At pre-planned intervals, the spacecraft will turn to point the high gain antenna at Earth and downlink the highly edited and compressed accumulated data. The raw data will be stored on board until such time as the science team concludes that it has been fully exploited or until it is over-written by a higher priority observation.

## 8. CONCLUSIONS

The most intriguing conclusion is that the likelihood of observing KBOs in all size categories is quite high. However, to successfully execute close flybys of small objects, a highly sophisticated, autonomous look-ahead and ma-neuver-to-encounter capability must reside on the space-craft. The long flight time coupled with the substantial on-board computing capability and memory allows the mission to take advantage of advances in software and data exploitation. En-route to Pluto the required sophis-tication can be developed and upgraded as knowledge and experience accumulates while transiting the Kuiper Belt.

A precision pointing mirror with a wide field of regard substantially increases the angular range of detection and survey, as well as the productivity of close encounter sci-ence. It would also enable much more frequent searches and greatly extend the life of the mission by reducing pro-pellant usage.

If the extended Pluto mission to the Kuiper Belt is deemed important, close attention should be paid to the $\Delta V$ bud-get to assure a high probability of sufficient post-Pluto encounter propellant to execute several KBO close en-counters.

A most intriguing possibility is that an incoming comet might be observed, far from the Sun and in a pristine or dormant state. If its ephemeris could be adequately deter-mined, it would permit observation from Earth years later on its perihelion pass and in its most active state.

The mission to Pluto provides the only near-term oppor-tunity to enter the Kuiper Belt. An extended mission to explore the Kuiper Belt would be a fascinating adventure into uncharted space and in the finest tradition of the great voyages of exploration.

### Acknowledgment

## 9. REFERENCES

[1] Committee on Planetary and Lunar Exploration, Space Studies Board, National Research Council, *Exploring the Trans-Neptunian Solar System*, National Acadamy Press, Washington, D.C. 1998

[2] R. Terrile, S. A. Stern, R. Staehle, S. Brewster, J. Carraway, P. Henry, H. Price,and S. Weinstein, *Space-craft Missions to Pluto*, Pluto and Charon, S. A. Stern and D. J. Tholen editors, The University of Arizona Press (USA), pg 103-124, 1997.

[3] P. Henry, R. Terrile, and J. Carraway, *Technology Se-lection and Design Requirements for Long Missions*, First IAA Symposium on Realistic Near-Term Advanced Sci-entific Space Missions, Turin, Italy, 25-27/6/1996.

[4] P. R. Weissman and H.F. Levison, Pluto and Charon, *Part V*, S. A. Stern and D. J. Tholen editors, The Univer-sity of Arizona Press (USA), pg 581, 1997.

[5] M. J. Duncan, H. F. Levison, and S. M. Budd, *The Dynamical Structure of the Kuiper Belt*, Astron. J. 110:3073-3081, 1995.

[6] A. L. Cochran, H. F. Levison, S. A. Stern and M. J. Duncan, *The Discovery of Halley-sized Kuiper Belt Ob-jects Using the Hubble Space Telescope*. Astrophys. J. 455:342-346, 1995.

[7] H. F. Levison and S. A. Stern, *Kuiper Belt Encounters With the Pluto-Charon Binary: A Mechanism for Excit-ing Charon's Eccentricity*, Lunar Plant. Sci. Conference. XXVI:841-842 (Abstract) 1995.

[8] D. Jewett and J. Luu,*The Solar System Beyong Nep-tune*, Astron. J. 109:1867-1876, 1995.

[9] C. Tombaugh, In Planets and Satellites, eds. G.P. Kuiper and B.M. Middlehurst, University of Chicago Press, 1961.

[10] C. Kowal, "*A Solar System Survey*," Icarus 77:118-123, 1989.